"Neutrino properties determined in the T2K oscillation experiment"

Ewa Rondio, on behalf of the T2K Collaboration

National Centre for Nuclear Research
Warsaw, Poland

Sixth Workshop on Theory, Phenomenology and Experiments in Flavour Physics – FPCapri2016

AnaCapri, June 10-13, 2016

How we try to understand neutrinos ?

- From sources to detectors (and in between)

- Neutrino oscillation was a surprise in 90's,
- now it is well-established phenomenon and a lot of efforts are made to determine its parameters
- In future it can be a tool for
  - beyond SM effects
  - CP-violation mechanism
  - Understanding matter-antimatter asymmetry

Neutrino oscillations - 3 flavours – picture as of today

Pontecorvo-Maki-Nakagava-Sakata (PMNS)mixing matrix

FLAVOR **MASS**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{+i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

”atmospheric”

SK, K2K, T2K, MINOS Nova

$$\Delta m^2_{31} = \begin{matrix}2.47\pm0.06\\-2.34\pm0.06\end{matrix}\times10^{-3}eV^2$$

$$\sin^2\theta_{23}(\Delta m^2>0)=0.437^{+0.033}_{-0.023}$$

$$\sin^2\theta_{23}(\Delta m^2<0)=0.455^{+0.039}_{-0.031}$$

CHOOZ, DayaBay, Reno, DblChooz, T2K

$$\sin^2\theta_{13}(\Delta m^2>0)=0.0234^{+0.0020}_{-0.0019}$$

$$\sin^2\theta_{13}(\Delta m^2<0)=0.0240^{+0.0019}_{-0.0022}$$

”solar”

SNO, KamLand, SK, Borexino

$$\Delta m^2_{21}=(7.54^{+0.26}_{-0.22})\times10^{-5}eV^2$$

$$\sin^2\theta_{12}=0.308\pm0.017$$

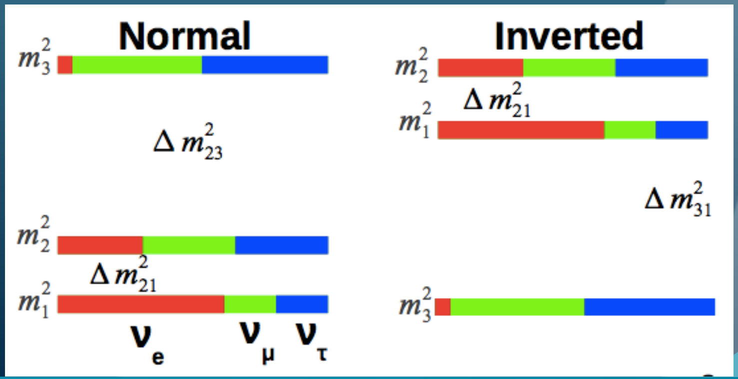
* $\Delta m^2_{ji} = m_j^2 - m_i^2$
Two free parameters for the three Δm^2's.
($\Delta m^2_{31}=\Delta m^2_{21}+\Delta m^2_{32}$)

Based on PDG2014

Mass hierarchy and matter effects

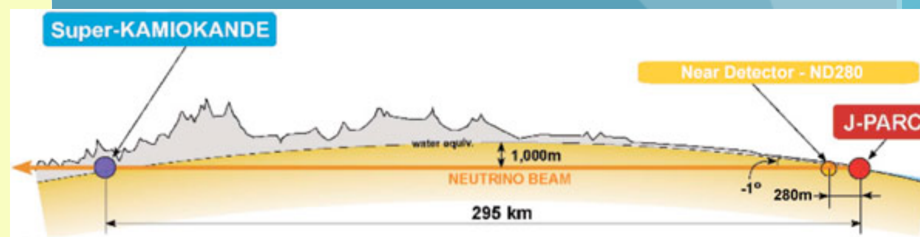
- Δm^2 – gives no information about absolute scale and on mass ordering
- In the Sun oscillations happen in dense matter
- Mikheyev–Smirnov–Wolfenstein (MSW) effect – matter influence - effect of electron density → effective mass of electron neutrino is changing
  - is raised for neutrino
  - is lowered for anti-neutrino
- Resonance enhancement appears at specific energies
- It depends on Δm^2 and electron density
- For Sun we observe resonance around 10 MeV
- From that we know that $m_1 < m_2$
- position of m_3 is not known

→ open question

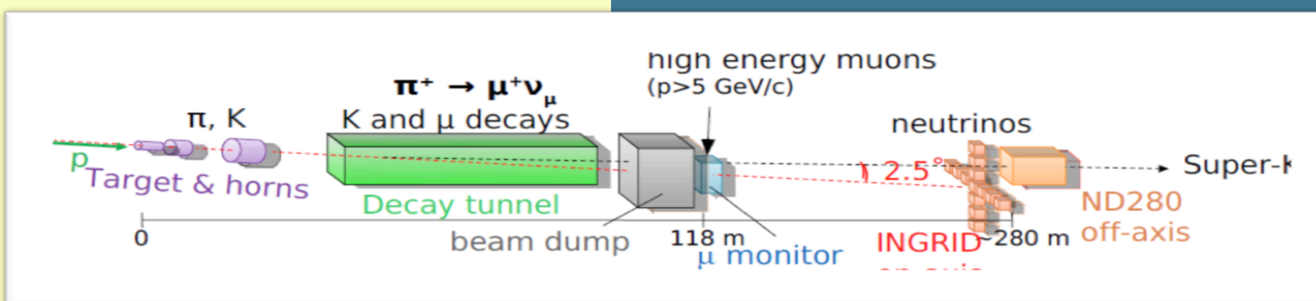


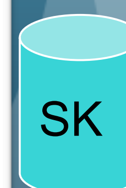
T2K experiment

- **Tokai-2-Kamioka**: long-baseline experiment with narrow-band beam
- **Muon neutrinos** produced in J-PARC laboratory in **Tokai** (30 GeV protons on graphite)



- **Near detector station** 280 m from the production point measures non-oscillated beam
- **Far detector** (295 km away) – **Super-Kamiokande**, water-Cherenkov detector in Kamioka mine





Main goal: neutrino **oscillation studies**

- muon (anti-)neutrino disappearance
- electron (anti-)neutrino appearance

… and ways of measuring θ_{13}

- disappearance -> **reactor experiments**

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$

$$P_{\rm sur} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267 \Delta m^2_{31} L/E),$$

Energy ~ a few MeV
Distance ~ km

- appearance -> **long-baseline experiments** with ν_μ beam

$$\nu_\mu \rightarrow \nu_e$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27 \Delta m^2_{23} L / E\right)$$

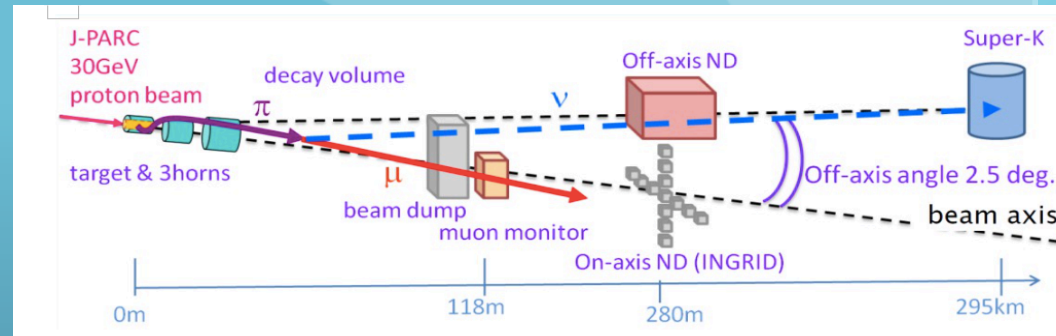
Leading terms!

Second order terms depend on δ and mass hierarchy

Energy ~ GeV
Distance ~ a few hundred km

Experimental set-up dedicated to measurements of oscillations with Δm^2_{23}

θ_{23} and θ_{13}



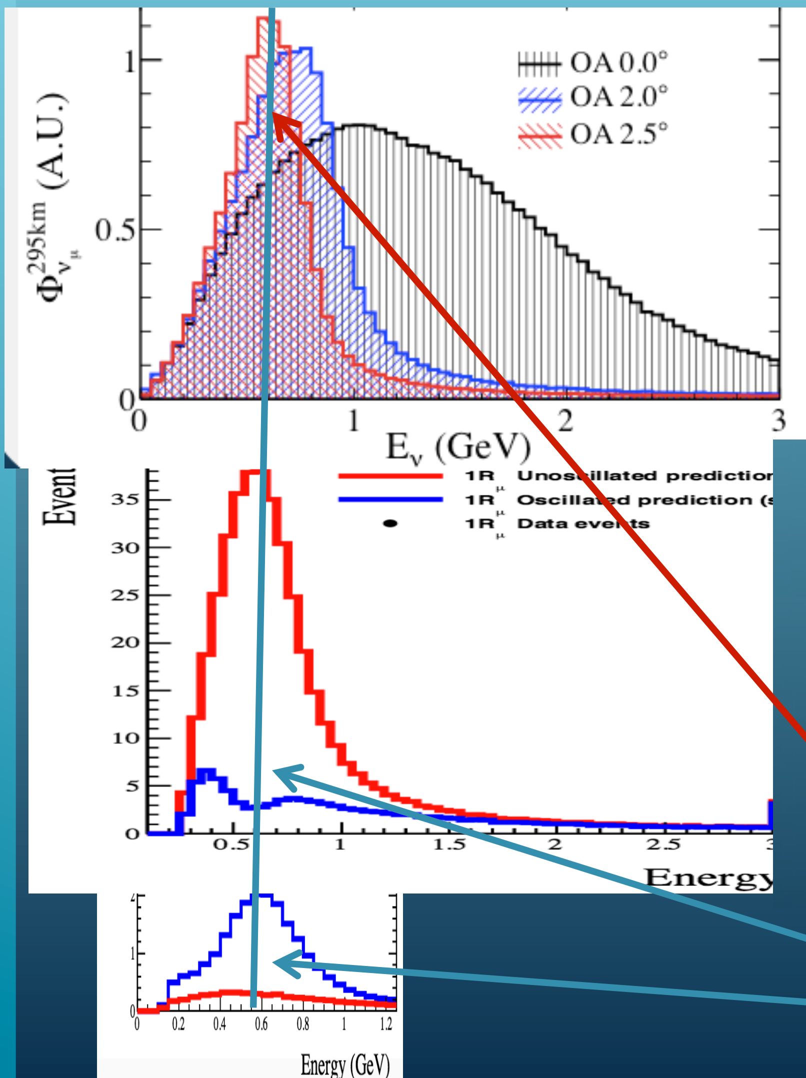
$$p + C \rightarrow \pi + \ldots K + \ldots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

Beam:
for precise predictions of neutrino fluxes good description of π, K production needed
(NA61data)



$2,5^{O}$ off axis beam selected
→ gives maximal oscillation effect
in disappearance
and in appearance at SK detector (295 km)

Data collection, result publication

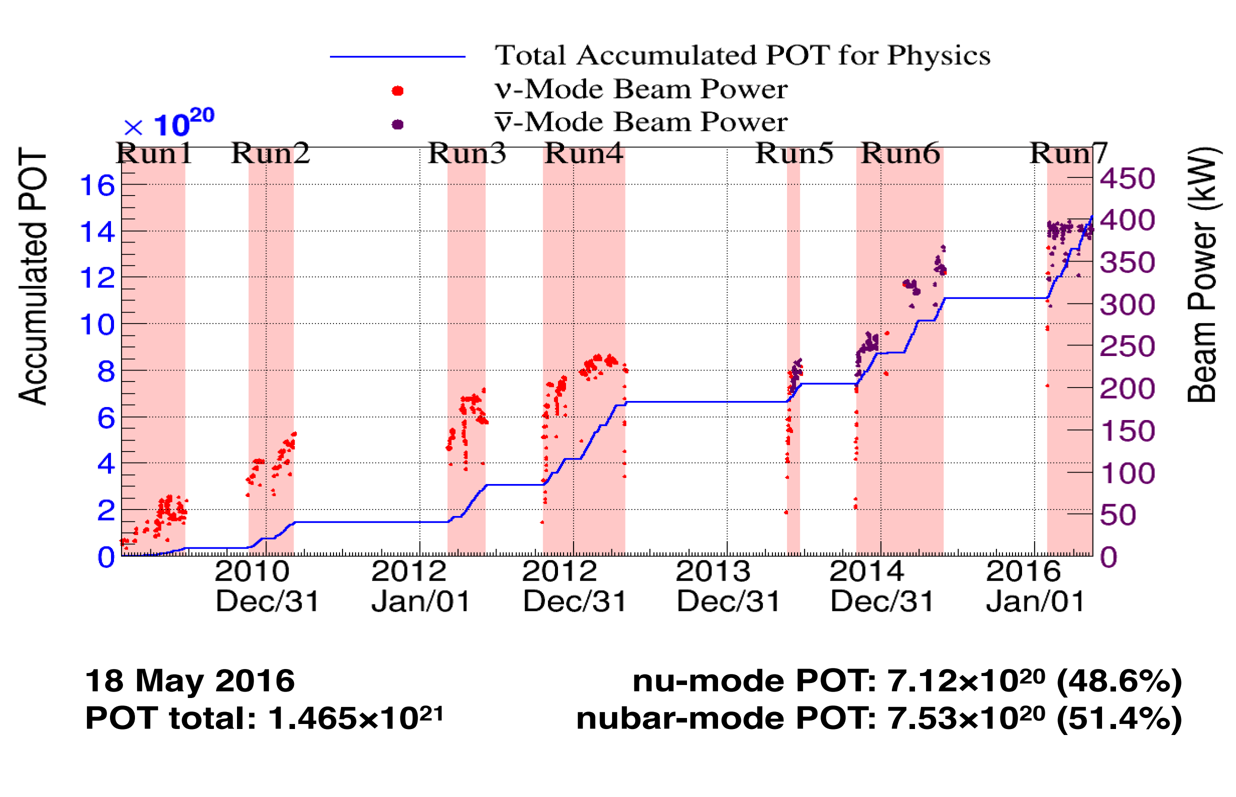
POT = Protons On Target

- $7.0 \cdot 10^{20}$ POT delivered in ν mode, $4.04 \cdot 10^{20}$ POT in anti-ν mode (till June 1, 2015)
- Goal: $7.8 \cdot 10^{21}$ POT

This year

- Maximum beam power achieved so far: 421 kW
- On May 27'th we achieved

$$\nu / \bar{\nu} = 50\% / 50\%$$



- Oscillation analyses released:

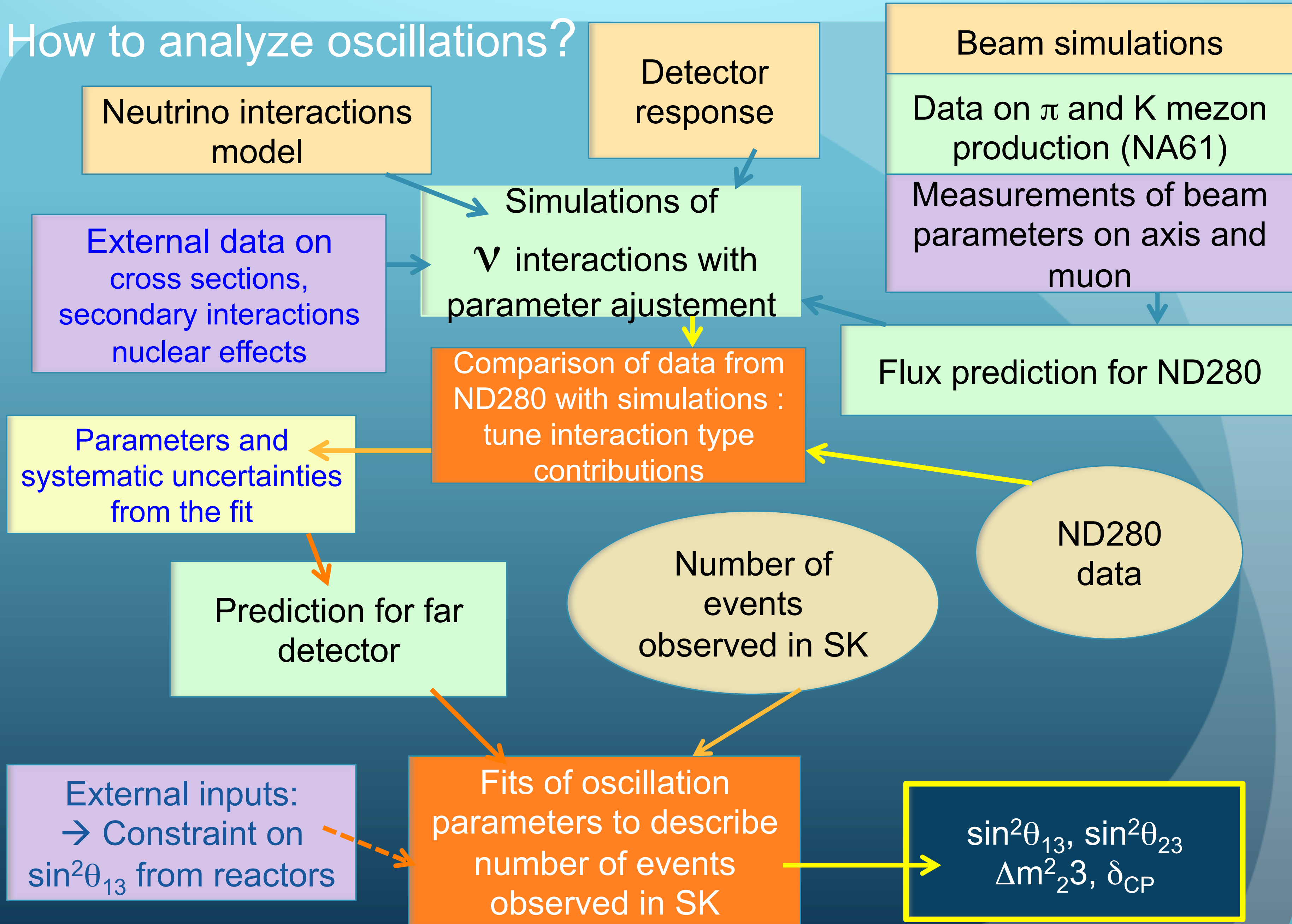
2010 data taking starts

- Jul 2011: ν_e app. 2.5σ
- Mar 2012: ν_μ 1st release
- Apr 2013: ν_e app. 3.1σ
- Aug 2013: ν_μ 2nd release
- Nov 2013: ν_e app. 7.3σ
- Feb 2015: joint nu fit, 1st constraint on δ_{CP}
- Dec 2015: anti-ν_μ 1st release

2011 **2012** **2013** **2014** **2015** **2016**

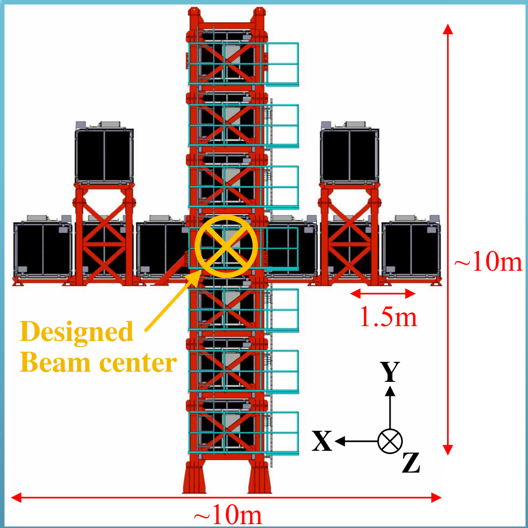
recent results

How to analyze oscillations?



Let's go through it step by step …….

Near detectors: INGRID and ND280

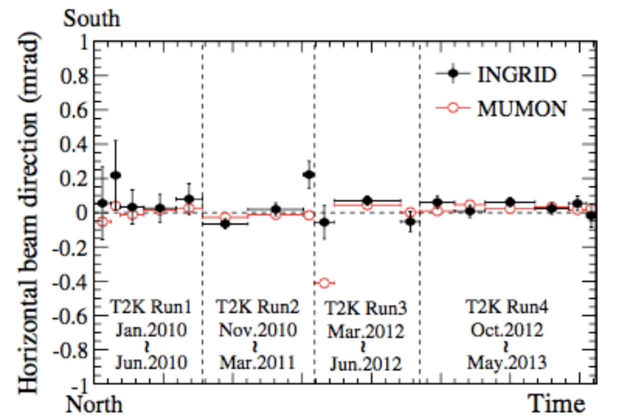


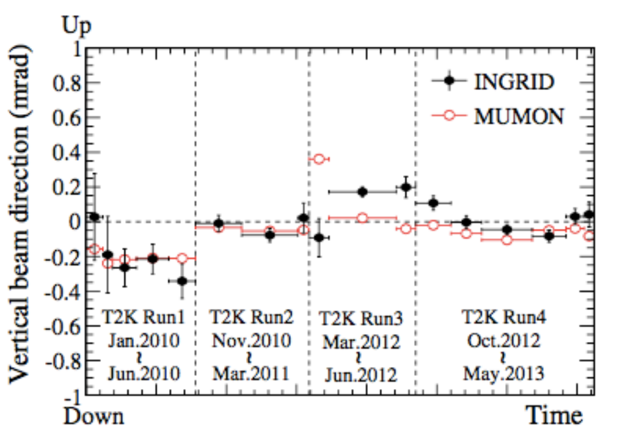
Detector on the beam axis
beam intensity and direction
→ stability control

Precision of direction measurement [mrad]

$$\bar{\theta}_X^{\text{beam}} = 0.030 \pm 0.011(\text{stat}) \pm 0.095$$

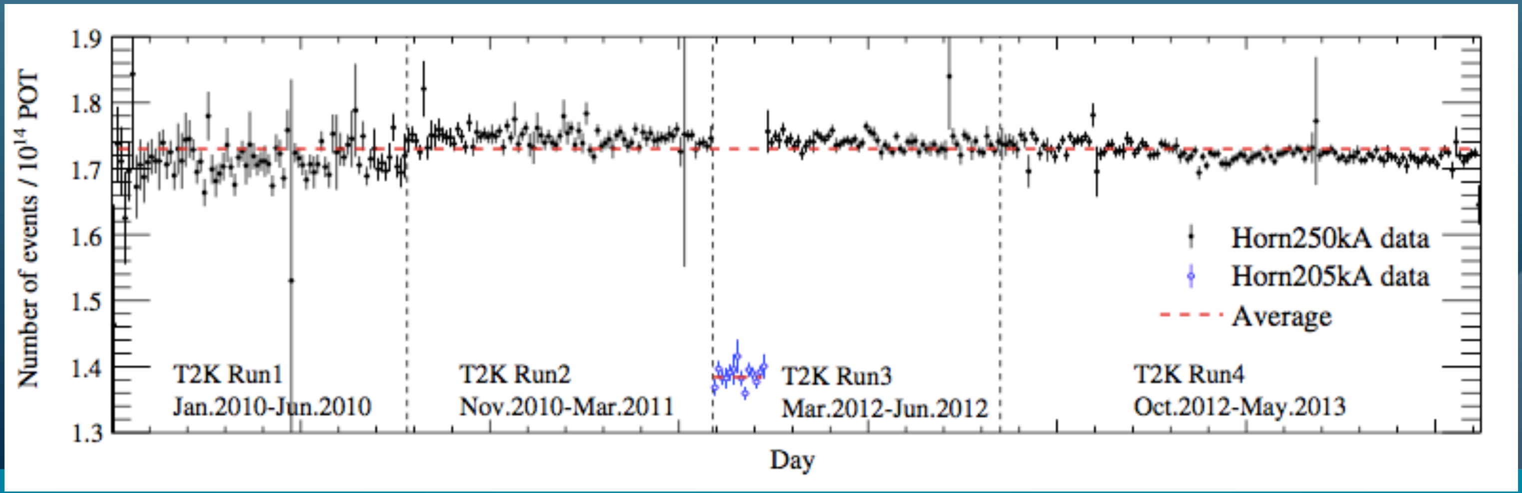
$$\bar{\theta}_Y^{\text{beam}} = 0.011 \pm 0.012(\text{stat}) \pm 0.105$$



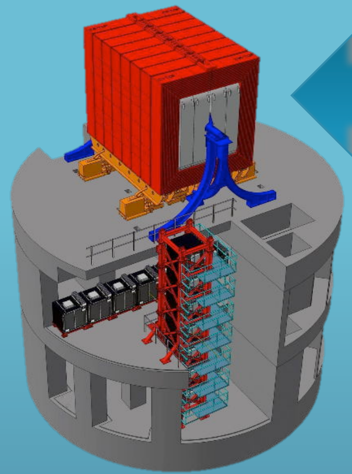


Ratio of events: observed/predicted

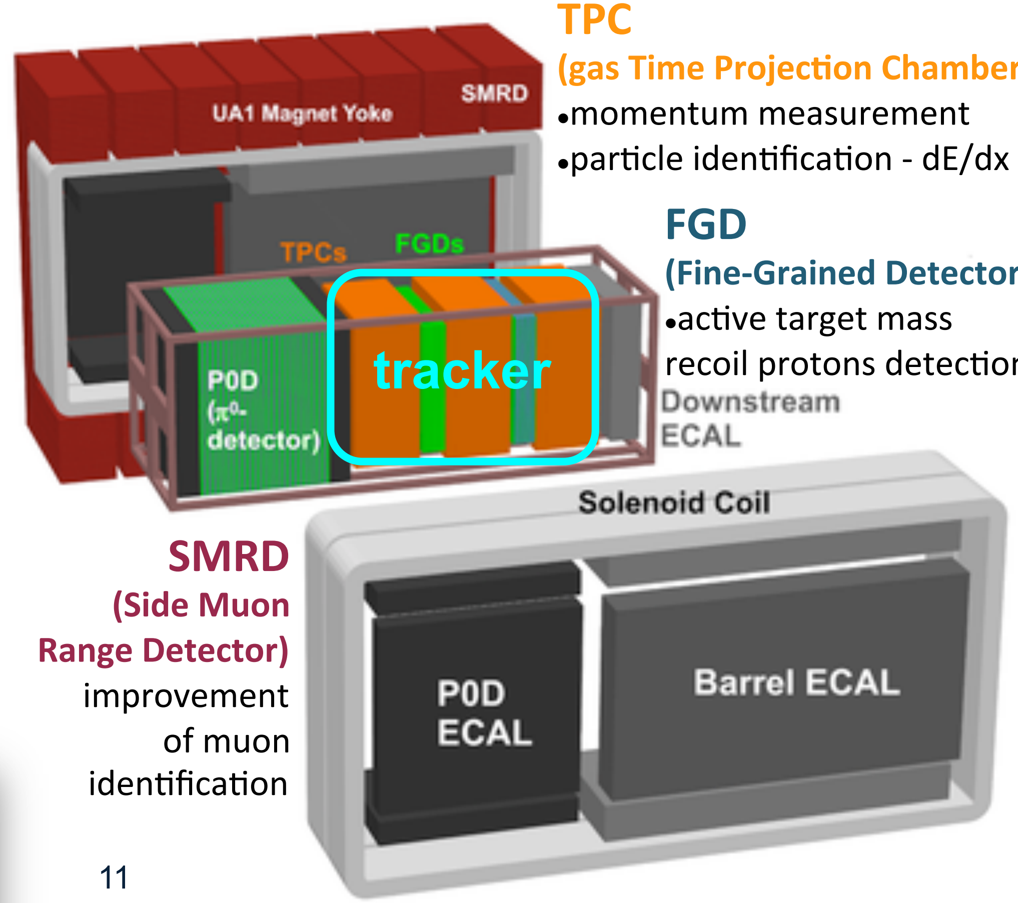
$$\frac{N^{\text{data}}_{250\text{ kA}}}{N^{\text{MC}}_{250\text{ kA}}} = 1.014 \pm 0.001(\text{stat}) \pm 0.009(\text{det syst})$$



Near detector - ND280



- Off-axis near detector
- ν_μ and ν_e flux measurement (constraints for oscillation measurements)
- Cross-section measurements (carbon, oxygen)

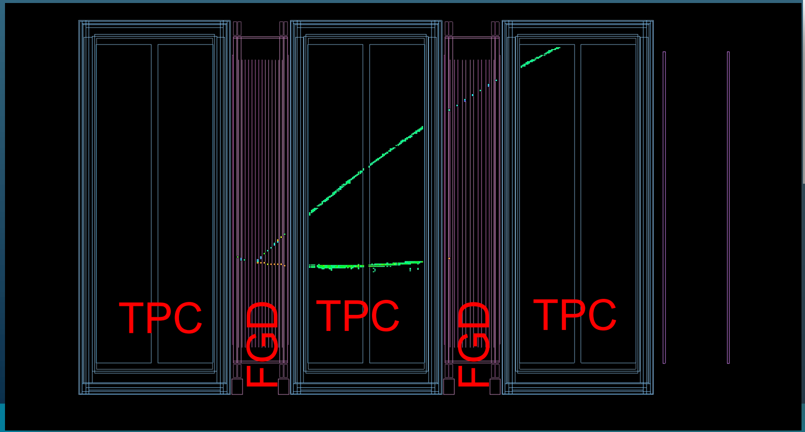


TPC
(gas Time Projection Chambers)
- momentum measurement
- particle identification - dE/dx

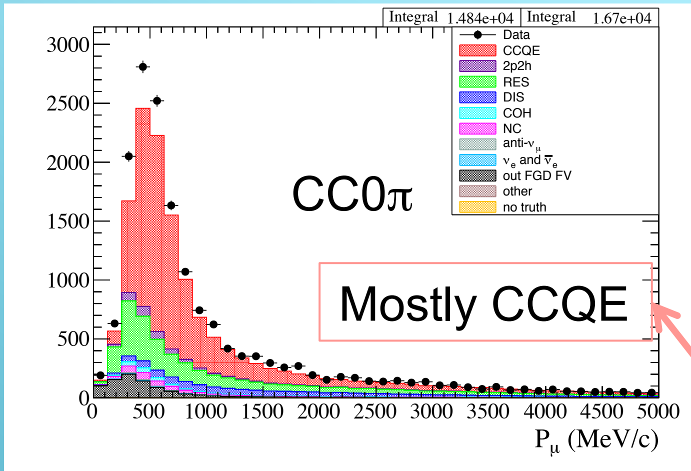
FGD
(Fine-Grained Detectors)
- active target mass recoil protons detection

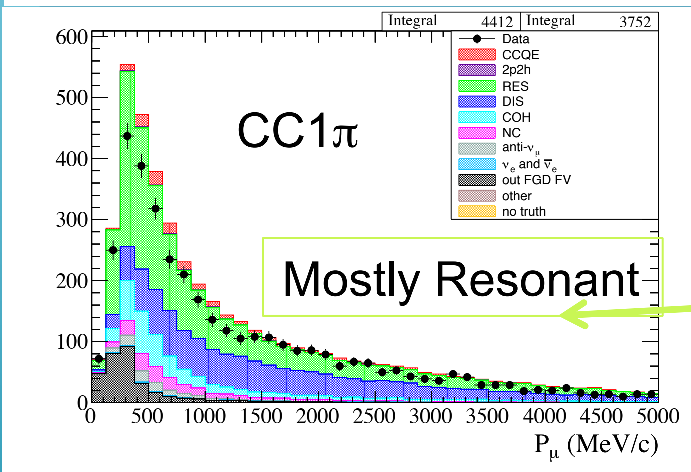
SMRD
(Side Muon Range Detector)
improvement of muon identification

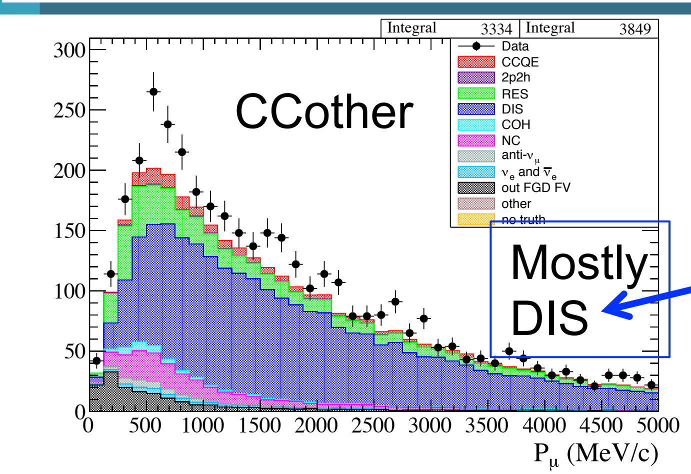
Data on event display (CC 2 track):



Same beam angle as for far detector – SK
Constraints on flux, cross-section and syst. for predictions at SK

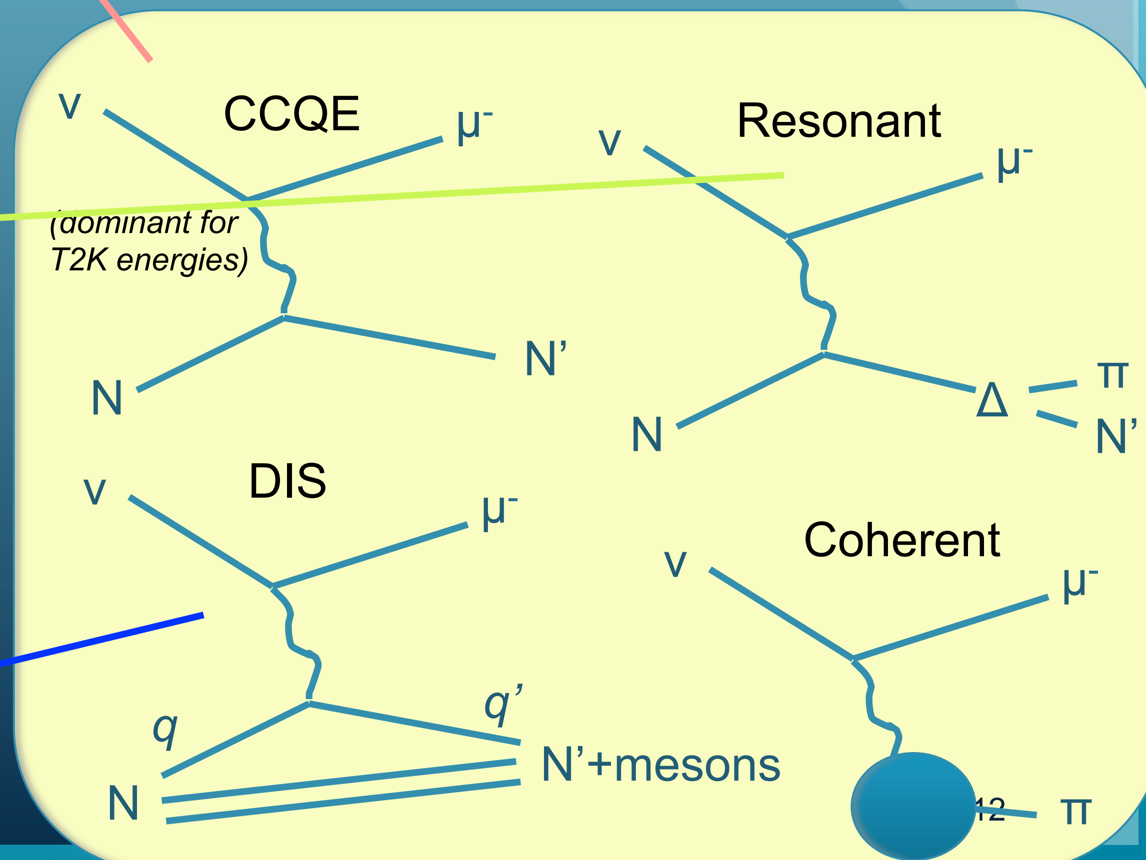






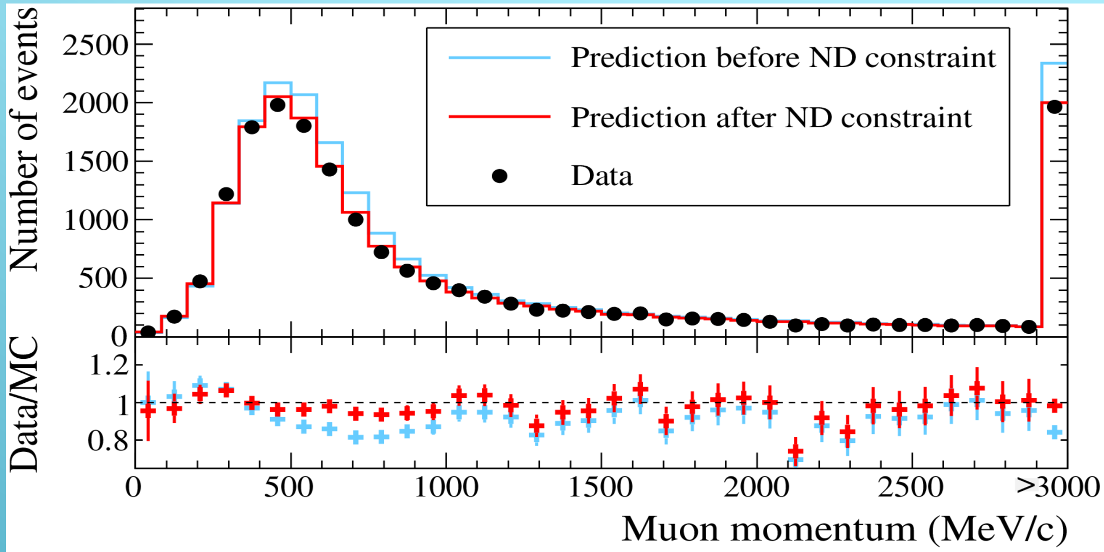
Here goal is to tune MC parameters as well as detector description to get good agreement for data and MC → fit model param. and systematics

Data in ND280 – selecting Charged-Current interactions
→ 3 categories (topology, not interaction type):
CC0π, CC1π$^+$, CC-other
and knowing how interaction types contribute
→ tune parameters, including fractions

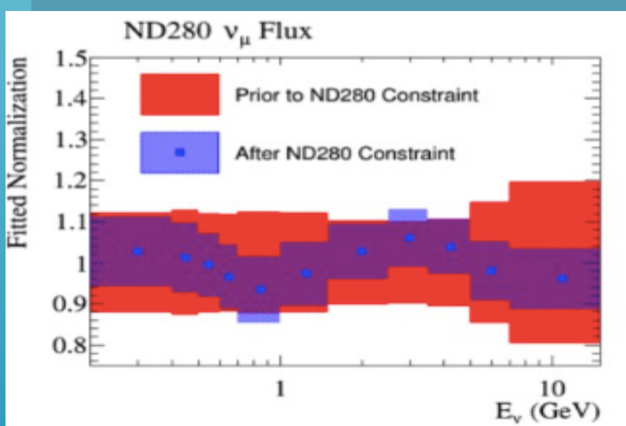


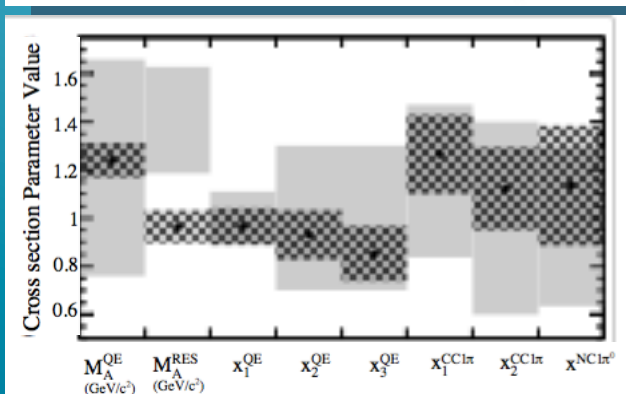
ND280 – fit

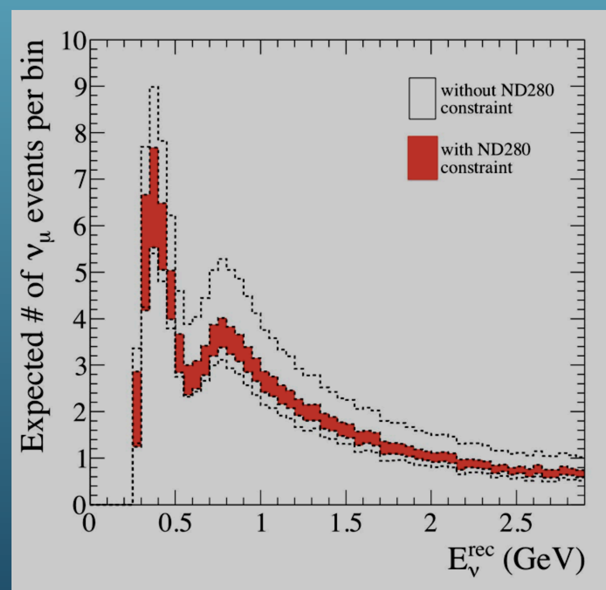
tune MC parameters
detector description
fit model param. and systematics

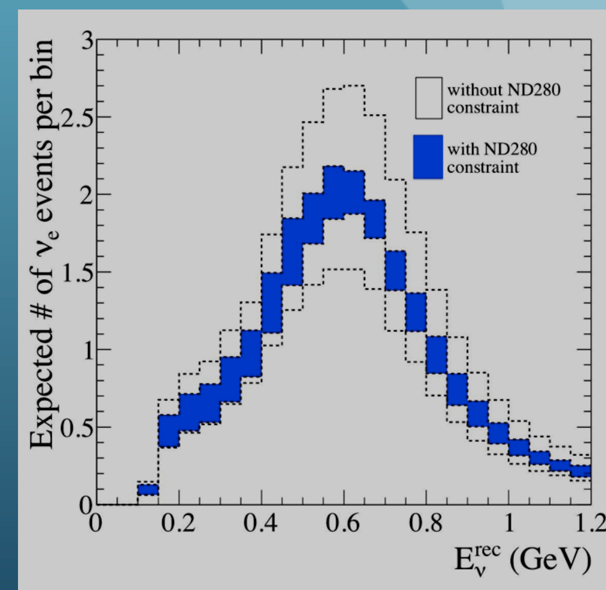


data used: from ND280 for three topologies momentum and angular distributions









taking best-fit parameters – predict number of events at far detector → from comparison with observation determine oscillation parameters

Systematic uncertainties on expected number of interactions in SK

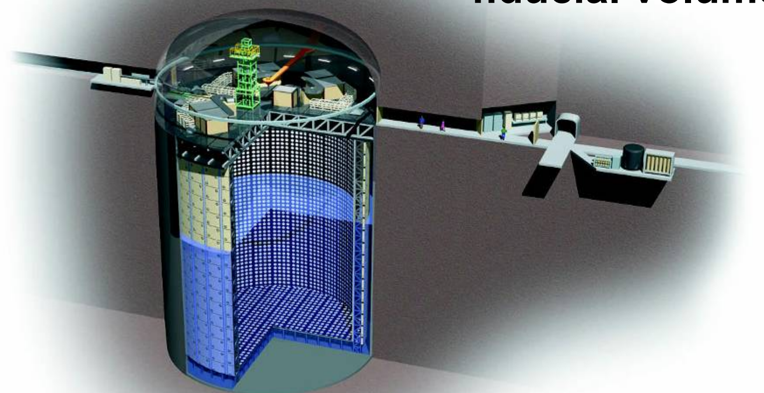
2014 ν | 2015 $\bar{\nu}$

T2K oscillation systematic (fractional) errors		ν_μ sample 2014	ν_e sample 2014	ν_μ sample 2015	ν_e sample 2015
ν flux		16%	11%	7.1%	8%
ν flux and cross section	without ND280 constraint	21.7%	26.0%	9.2%	9.4%
	WITH ND280 constraint	2.7%	3.2%	3.4%	3.0%
independent cross sections (different nuclear targets)		**5.0%**	**4.7%**	***10%**	***9.8%**
Final State Interaction / Secondary Interaction at Super-K		3.0%	2.5%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
Total	without ND280 constraints	23.5%	26.8%	14.4%	13.5%
	WITH ND280 constraints	**7.7%**	**6.8%**	***11.6%**	***11.0%**

* including uncertainties on effects of multi-nucleon interactions (MEC)

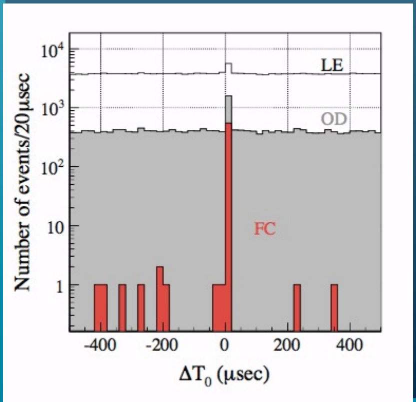
Far detector - Super-Kamiokande

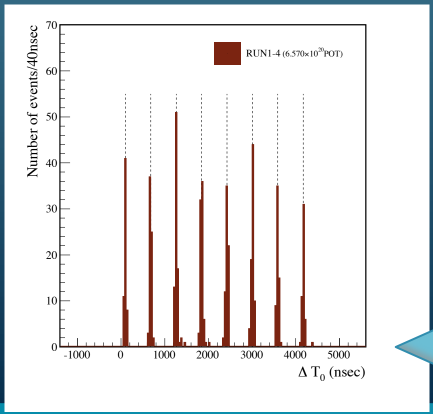
50 kton of water, 22.5 kton fiducial volume

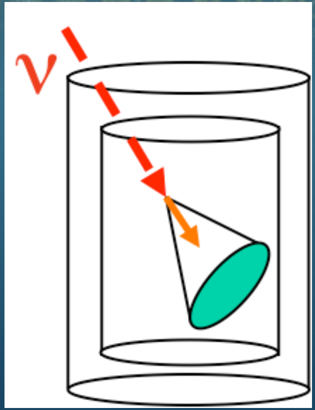


>11,000 photomultipliers on the walls observe Cherenkov light

beam events selected based on time correlation







Single ring – candidate for lepton from CC interaction

If track contained in SK (FC)

→ energy measured

→ assuming CCQE one can calculate ν energy

FC events within beam spill window accidentals < 1%

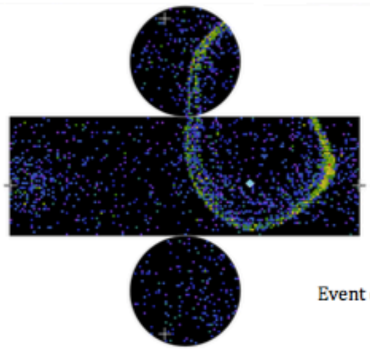
Observation in Super-Kamiokande

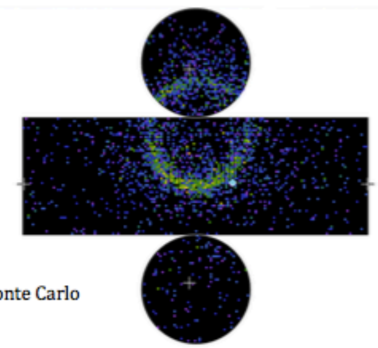
μ-like

- Single reconstructed muon-like ring
- $P_{\mu} > 200$ MeV/c
- One or less decay electrons

e-like

- Single reconstructed electron-like ring, with $E_{visible} > 100$ MeV
- Reconstructed $E_{neutrino}$ <1250 MeV
- No decay electrons
- Not π_0-like





Event displays from Monte Carlo

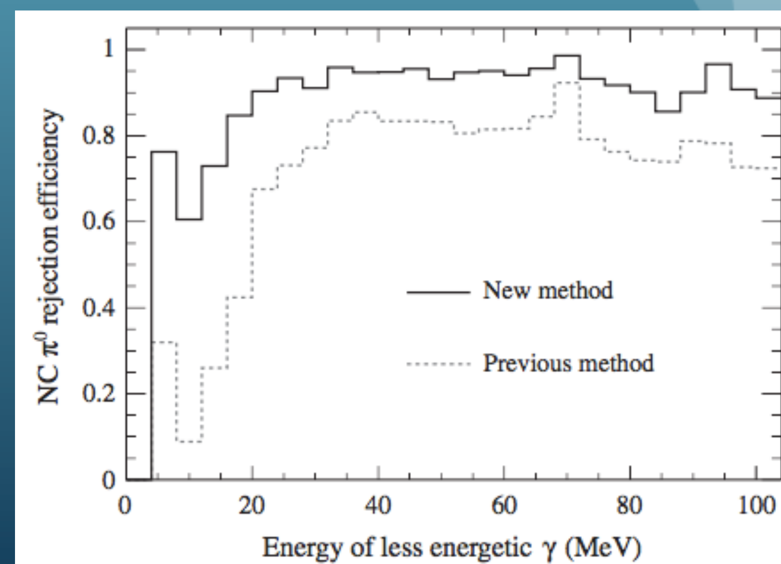
Selecting candidates for CC ν_{μ} and CC ν_e

→ decay electron could signal invisible π

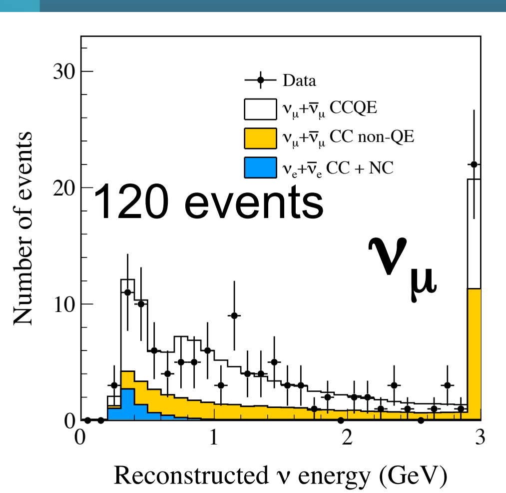
→ not π^0 – like

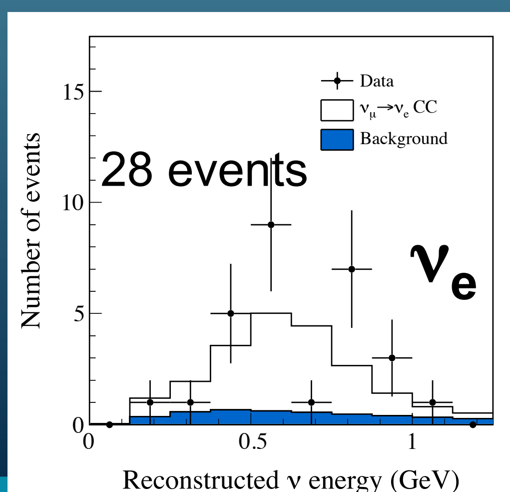
dedicated tools used to search for π^0 's between e-like single ring events

→to reduce contribution from NC ν_{μ} with π^0 production where one ring is not reconstructed or overlaps



Important improvement in purity of ν_e selected sample

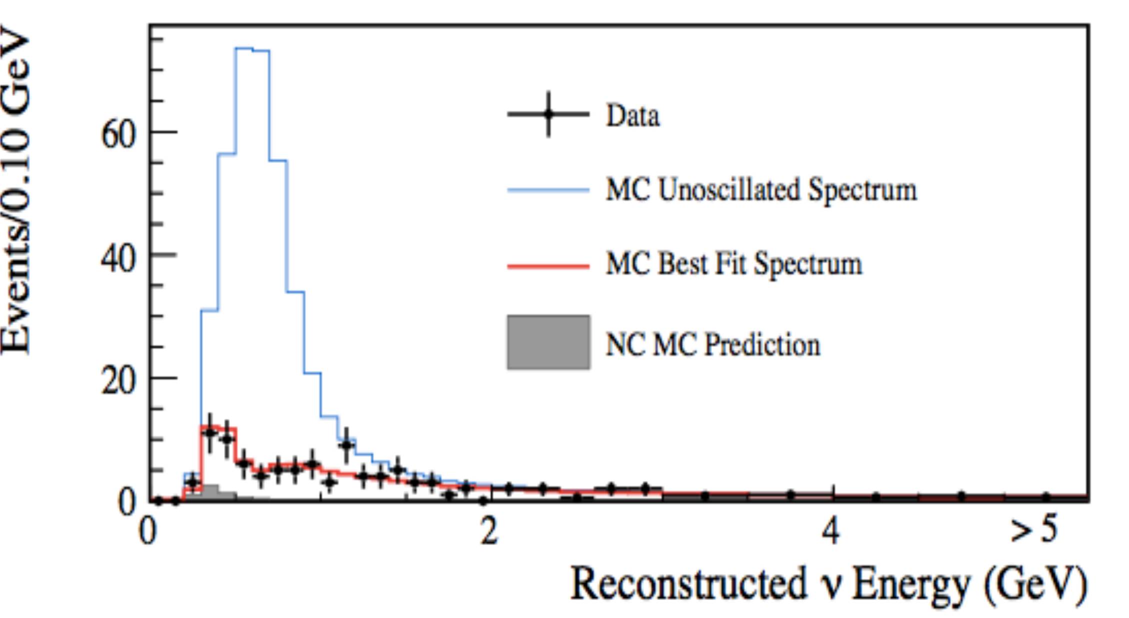


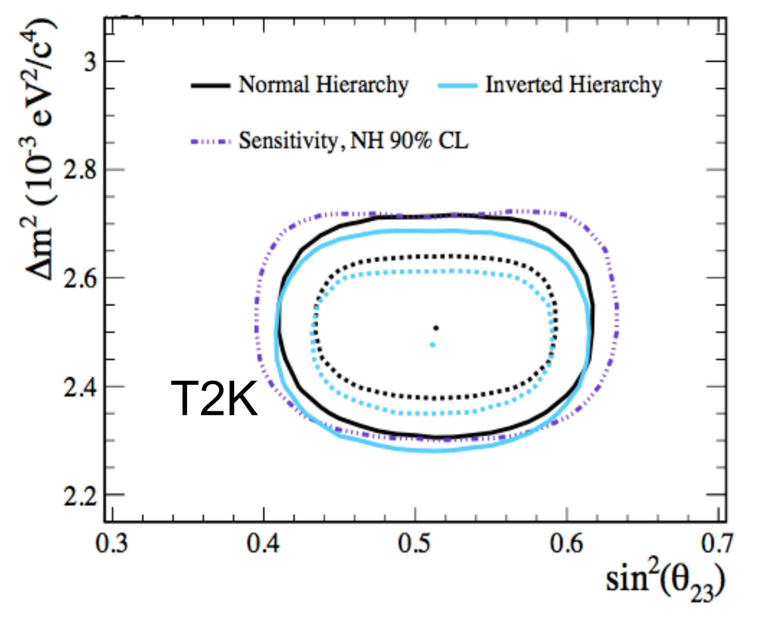


measurement of $\Delta m_{23}{}^2$, θ_{23}

PHYSICAL REVIEW D 91, 072010 (2015)

for ν_μ events – compare observed with expectation of oscillated flux → Δm^2_{23}, θ_{23}

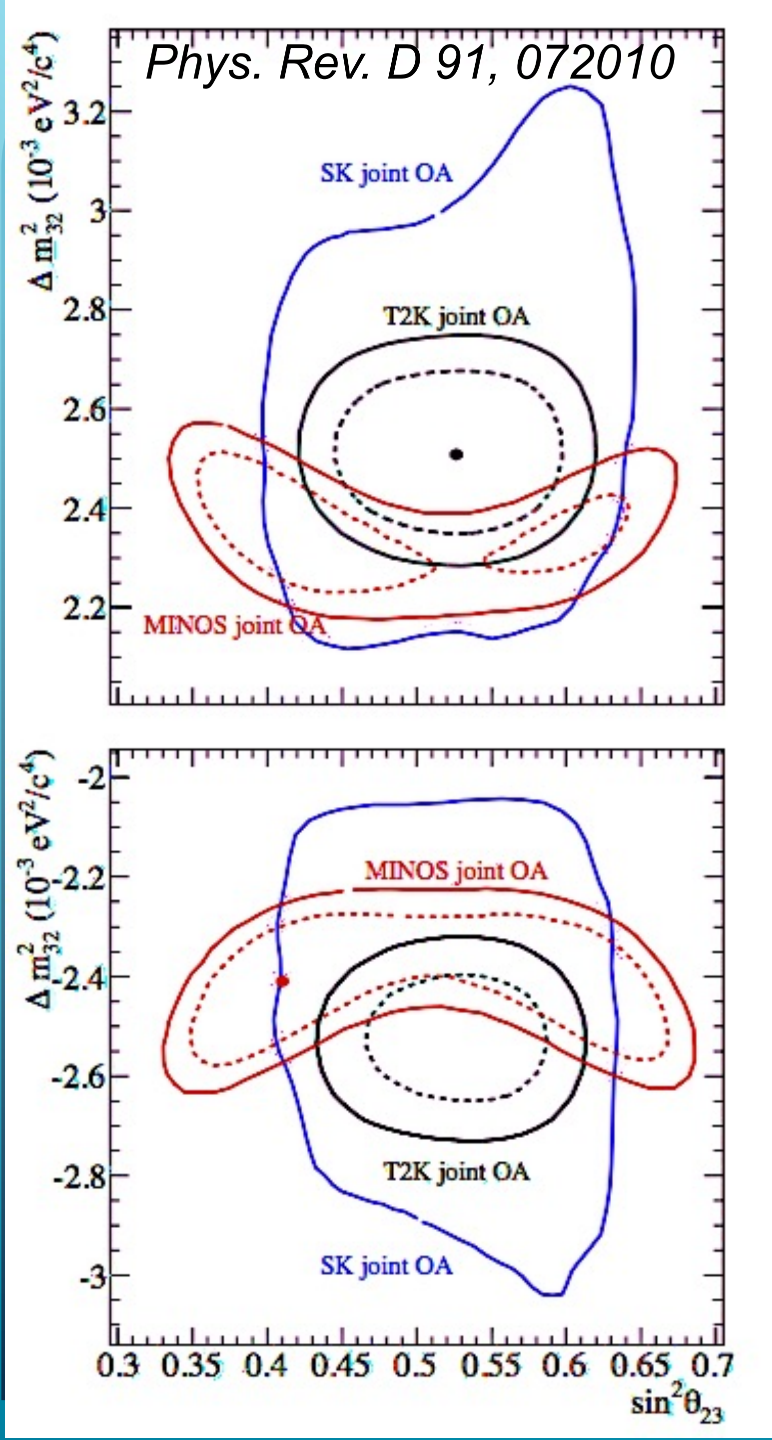


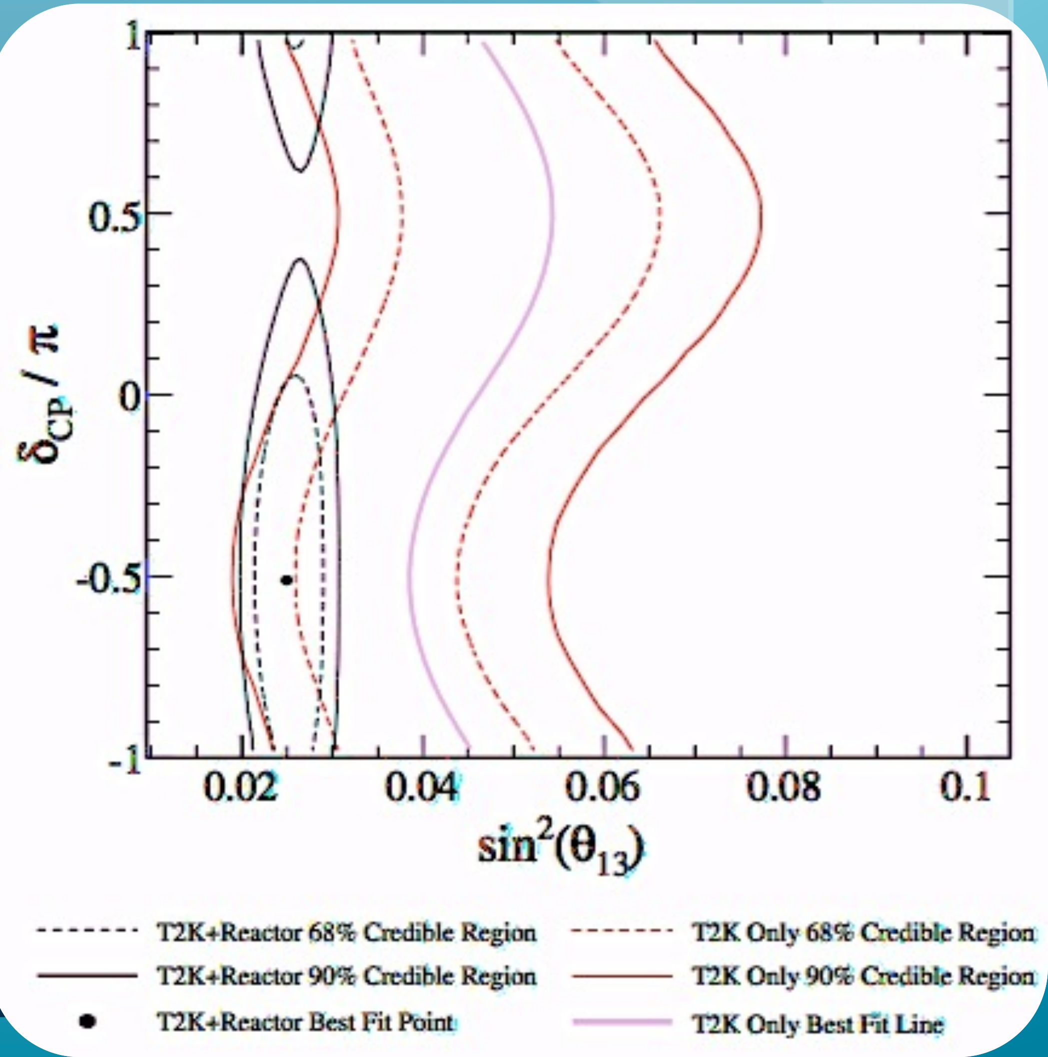


using both samples in combined analysis – $|\Delta m^2|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP} are determined while values for $\sin^2\theta_{12}$ and Δm^2_{21}, are taken from "solar" best fits.

- predictions are done for normal and inverted mass hierarchy
- analysis can be done using ν reconstructed energy or charged lepton momentum and angle with respect to the beam direction.
- for best precision – constraint from reactor experiments on $\sin^2\theta_{13}$ is used

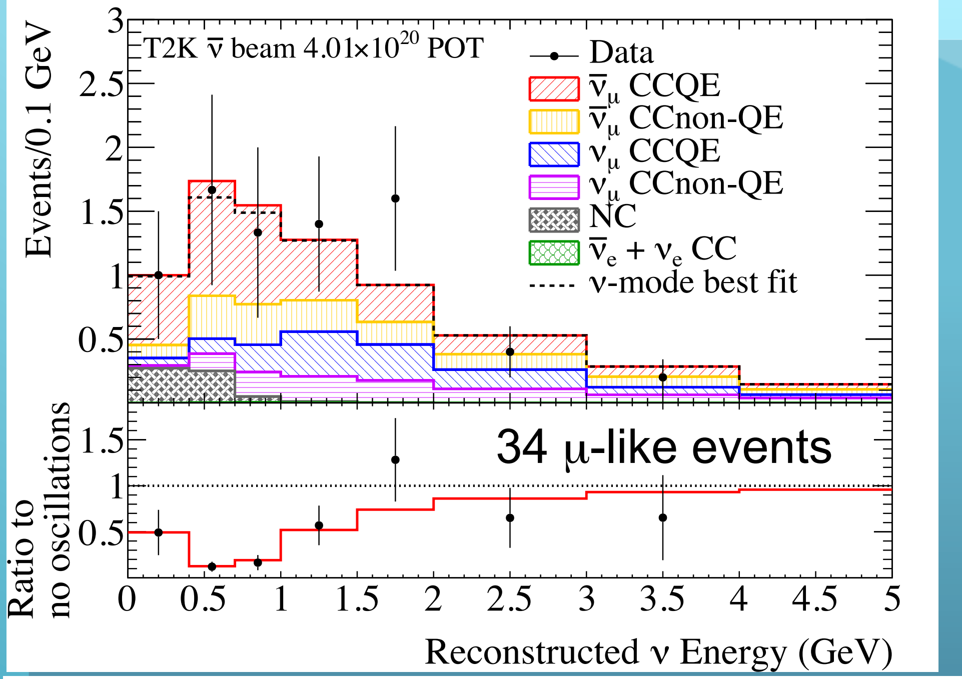
Summary of the results for 2-3 and 1-3 sectors from global fits

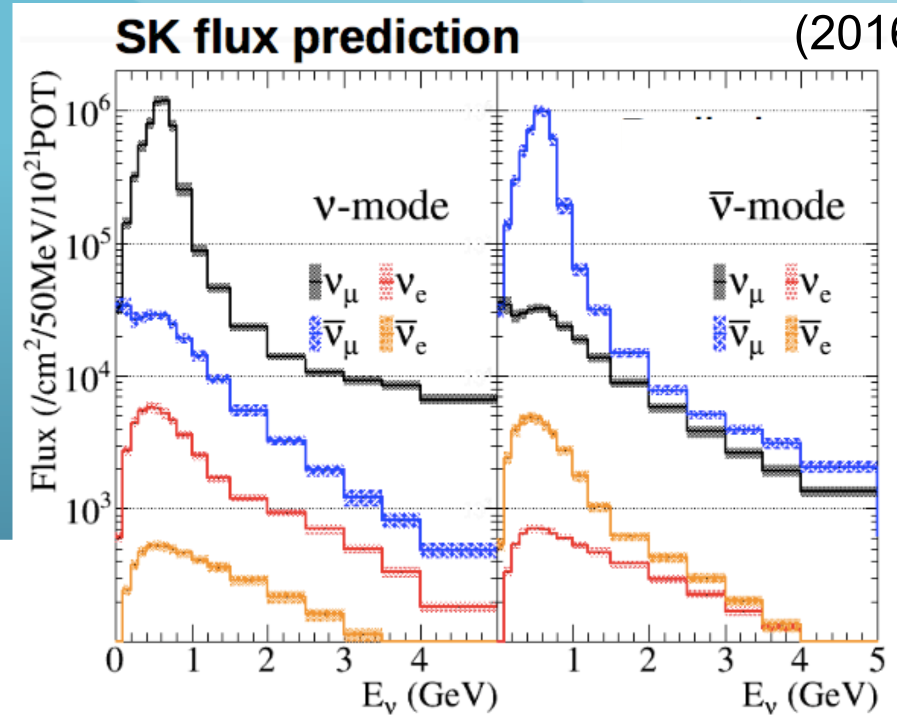


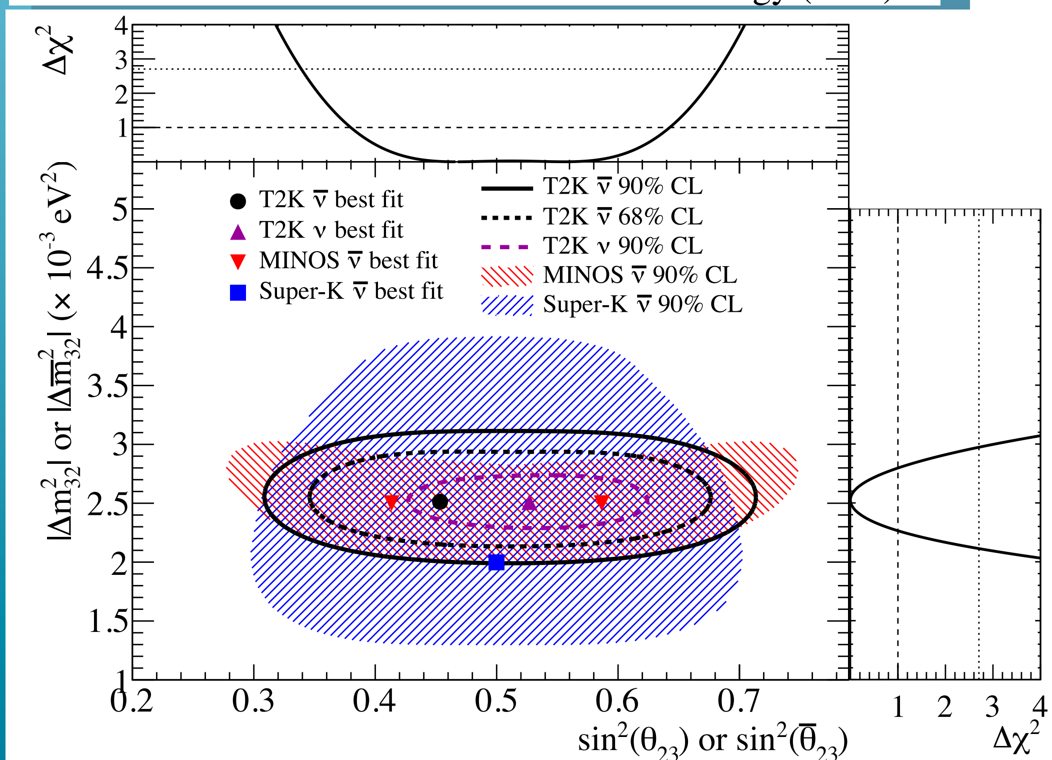


$\overline{\nu}$ beam – results

PRL 116, 181801 (2016)







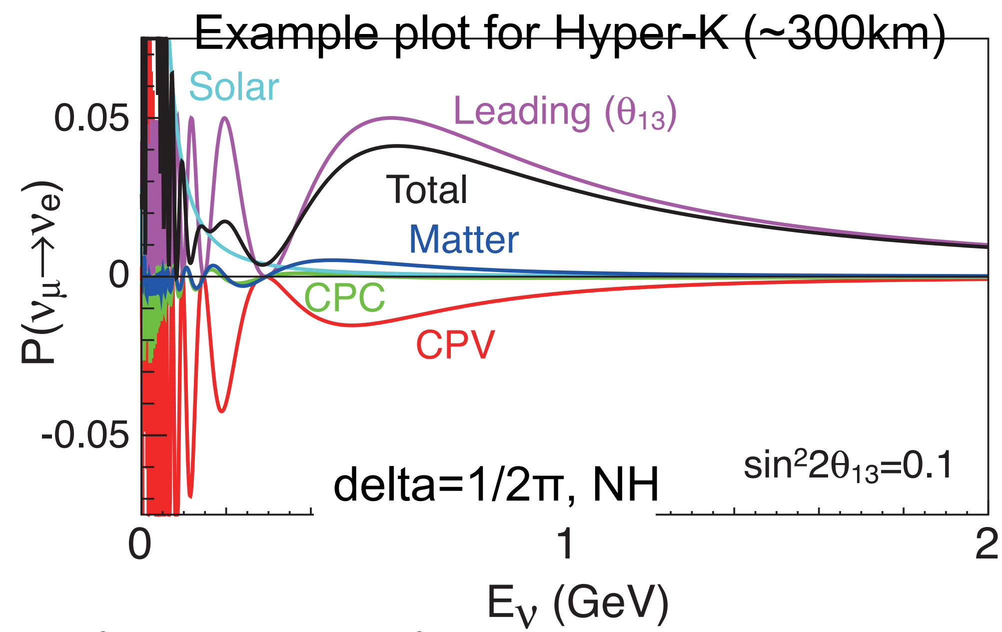
Analysis for 4,01*10^{20} POT with anti-nu beam mode

Disappearance: parameters consistent with
- maximal mixing
- neutrino parameters
- other experiments

Appearance – 3 e-like events seen
more data needed

Perspectives for CPV and MH

- Looking for appearance



$$P(\nu_\mu \rightarrow \nu_e) \quad vs. \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$P(\nu_\mu \rightarrow \nu_e) \approx 4c_{13}^{2}s_{13}^{2}s_{23}^{2}\sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$ Leading including matter effect

$$+8c_{13}^{2}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP conserving

$$-8c_{13}^{2}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP violating

$$+4s_{12}^{2}c_{13}^{2}(c_{12}^{2}c_{23}^{2}+s_{12}^{2}s_{23}^{2}s_{13}^{2}-2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$ Solar

$$-8c_{13}^{2}s_{13}^{2}s_{23}^{2}(1-2s_{13}^{2})\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$ Matter effect (small)

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

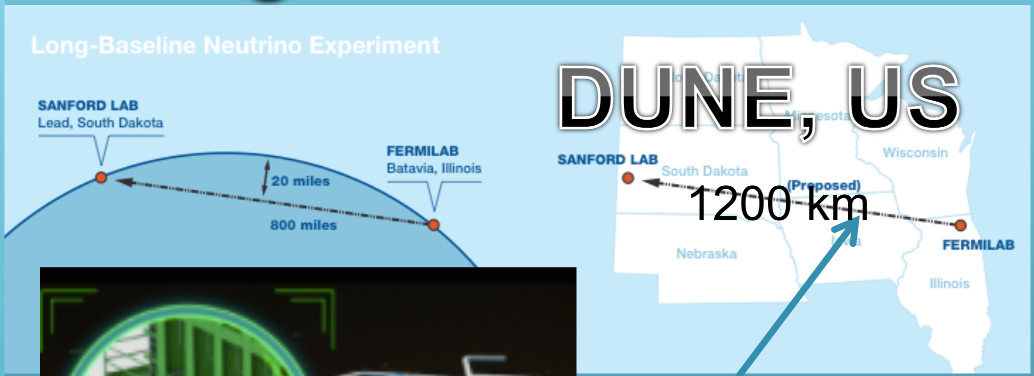
$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$

replace δ by $-\delta$ and a by $-a$ for $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

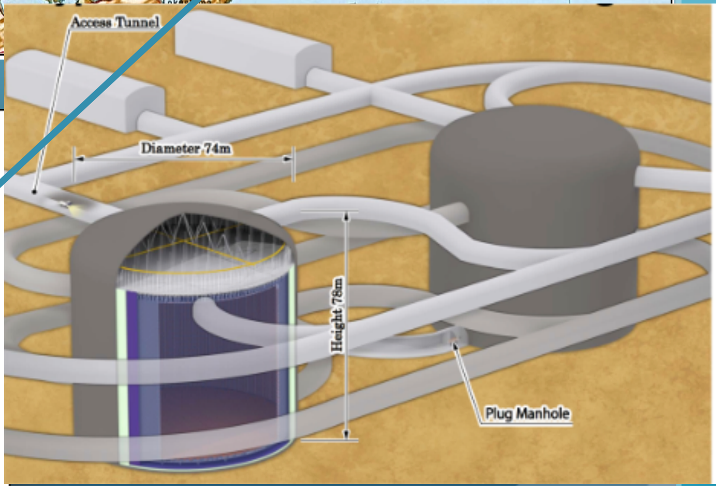
Long Baseline Future

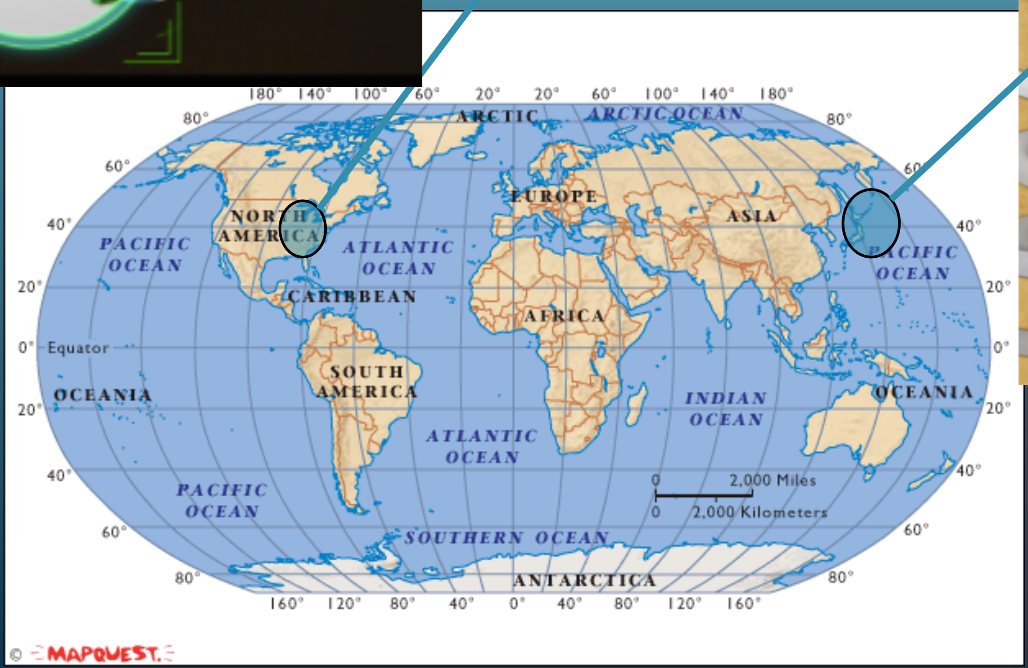
Long term
ie. after/around 2025

DUNE, US



Hyper-Kamiokande, Japan





Summary:

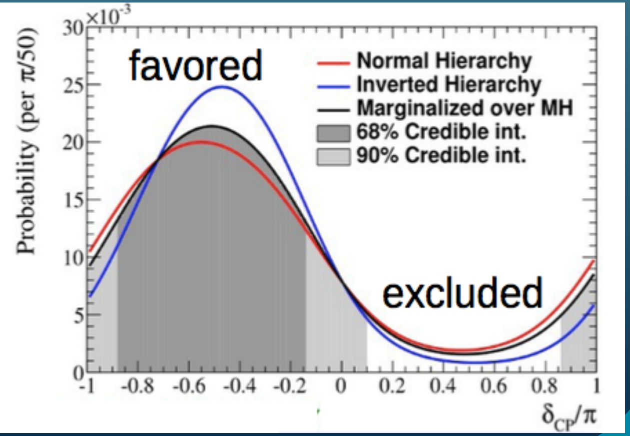
$\theta_{23} = 45.8 \pm 3.2°$
$\theta_{12} = 33.46 \pm 0.85°$
$\theta_{13} = 8.51 \pm 0.23°$

$\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5}\ eV^2$
$|\Delta m^2_{32}| = (2.44 \pm 0.06) \cdot 10^{-3}\ eV^2$
δ_{CP} = some hints

PLEASE CONTINUE TO ENJOY ^ NEUTRINO OSCILLATIONS

precision measurements of

to get better knowledge on …



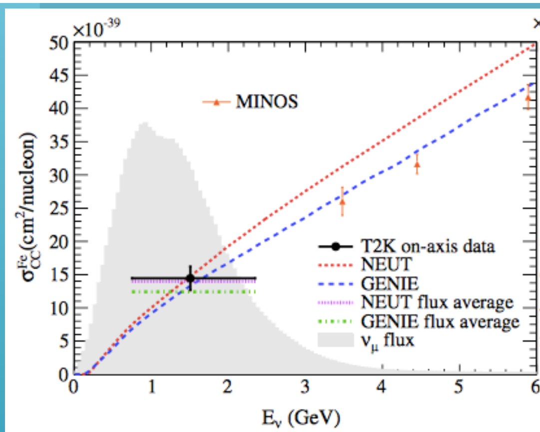
and more….

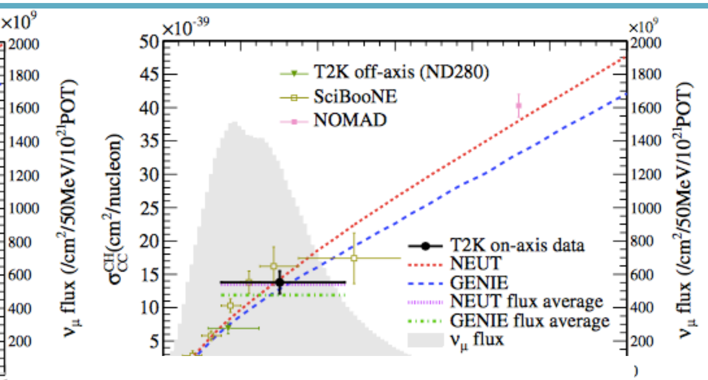
T2K phase II and Hyper-K welcome new, enthusiastic collaborators …

Improvements require better knowledge of interactions, better cross section measurements to test models

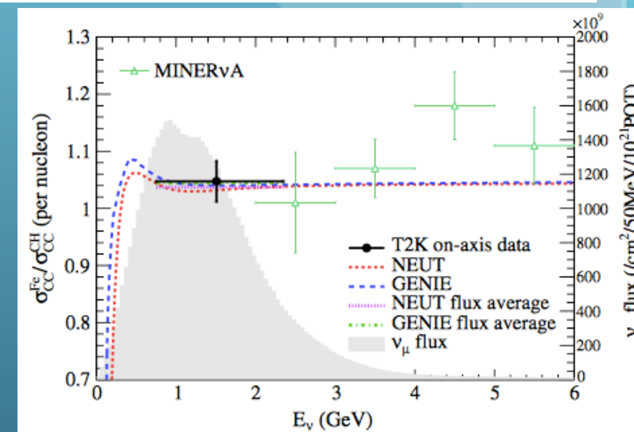
INGRID

Measurement of the inclusive ν_μ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam

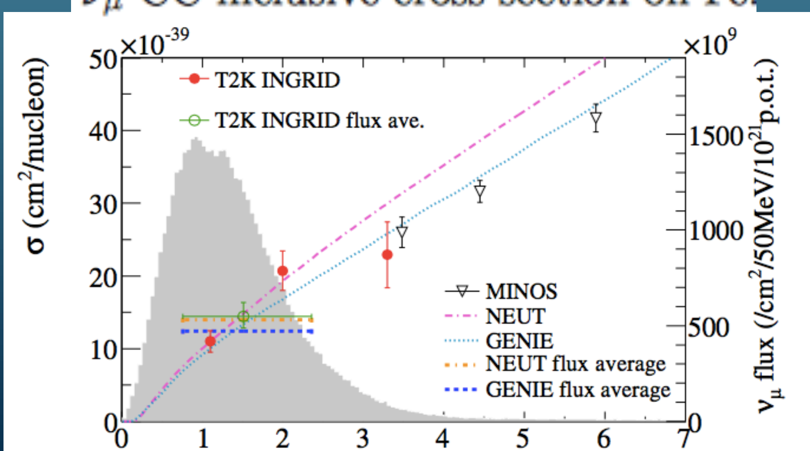




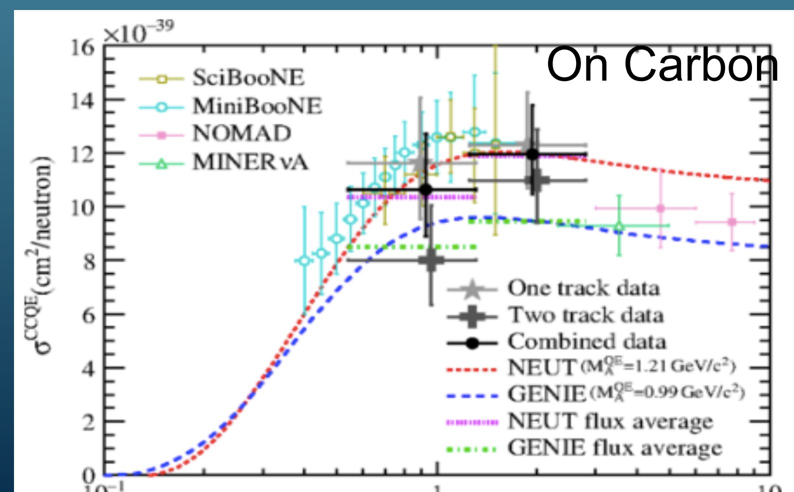
Phys. Rev. D, 90, 052010 (2014)



ν_μ CC inclusive cross section on Fe.



arXiv:1509.06940v1 [hep-ex]

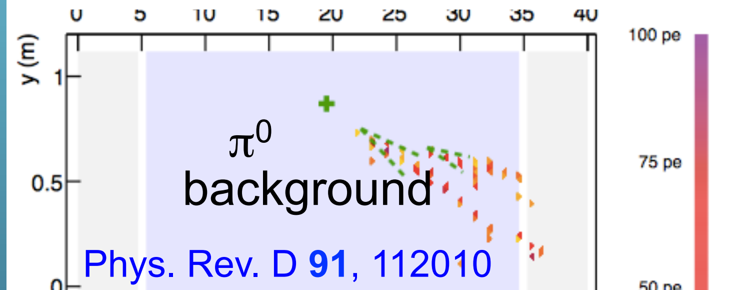


Phys. Rev. D **91**,112002

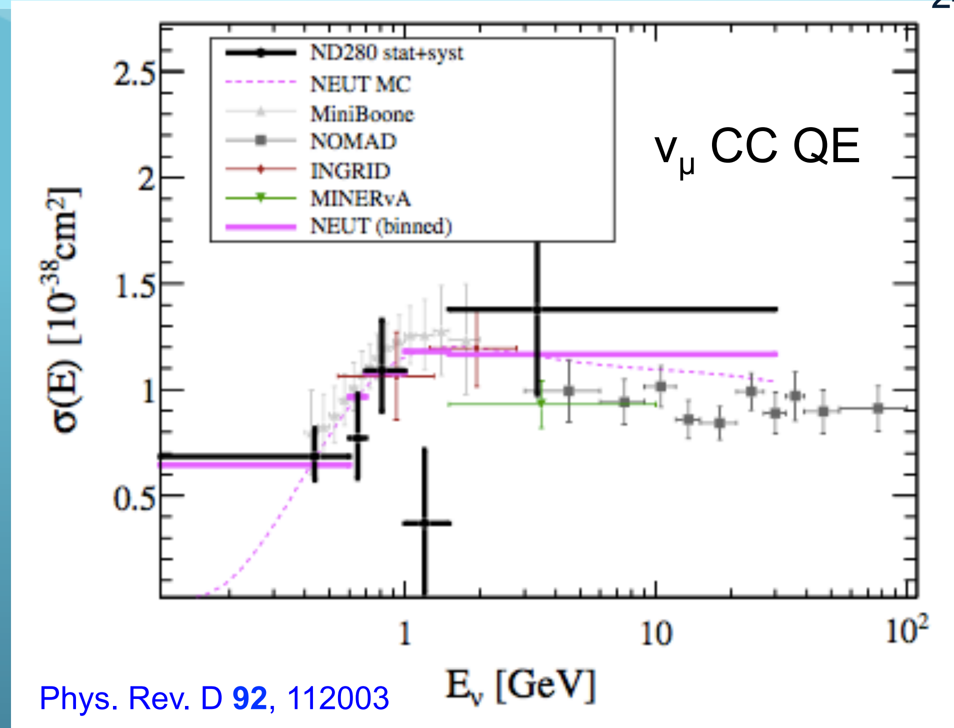
ND280 data

important information for analysis

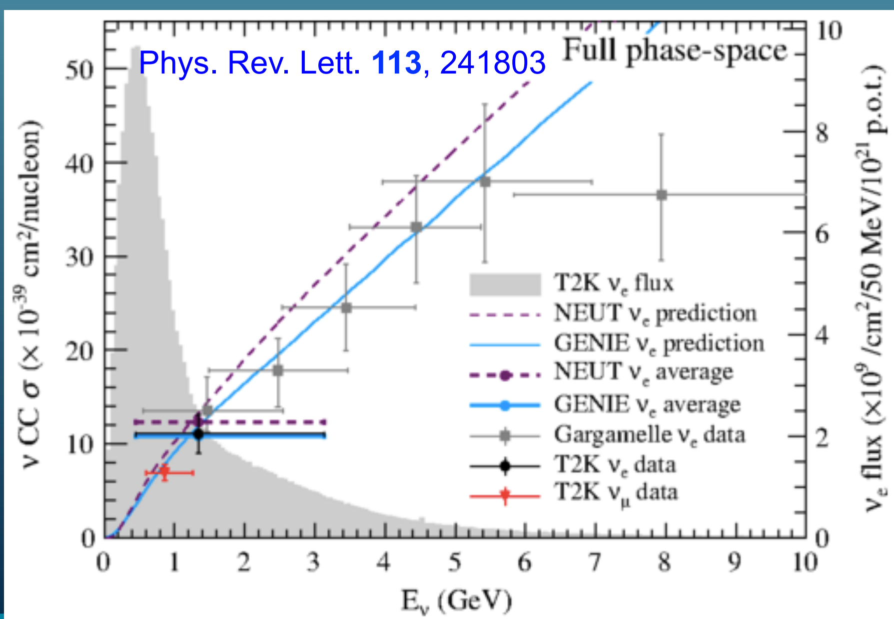
$R_{water} = 0.89 \pm 0.08\ (\text{stat.}) \pm 0.11\ (\text{sys.})$



Phys. Rev. D **91**, 112010



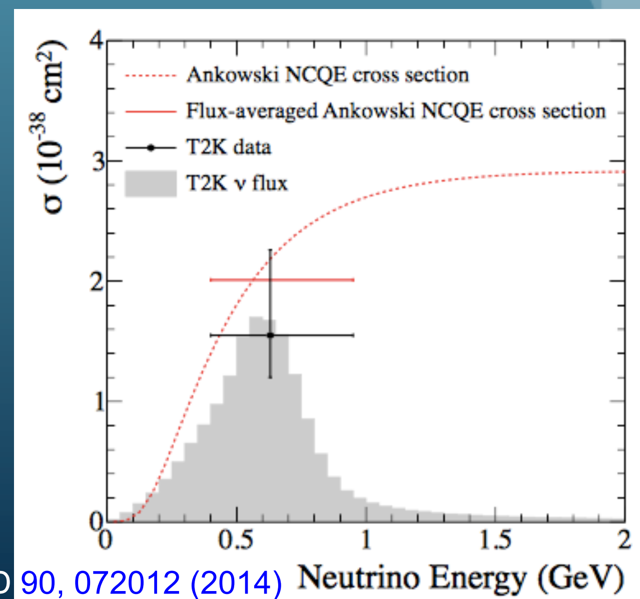
Phys. Rev. D **92**, 112003



Phys. Rev. Lett. **113**, 241803

and SK

NC QE



Phys. Rev. D 90, 072012 (2014)

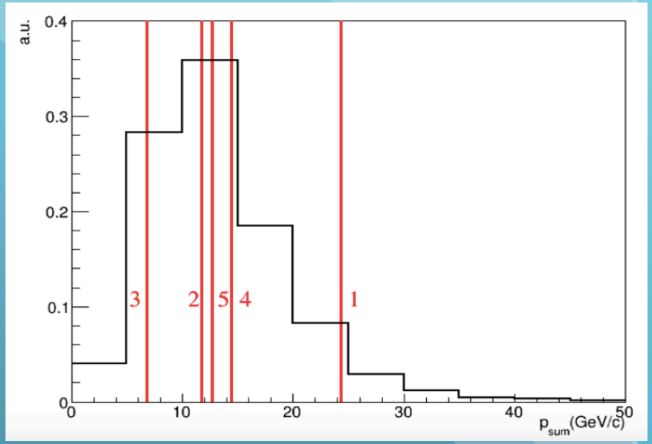
Observation of all expected transitions

appearance $\nu_\mu \rightarrow \nu_\tau$ OPERA

5 ν_τ CC candidates found, with 0.25 events background

exclusion of background-only hypothesis: 5.1 σ

discovery of ν_τ appearance



Sum of momenta of charged part and gammas

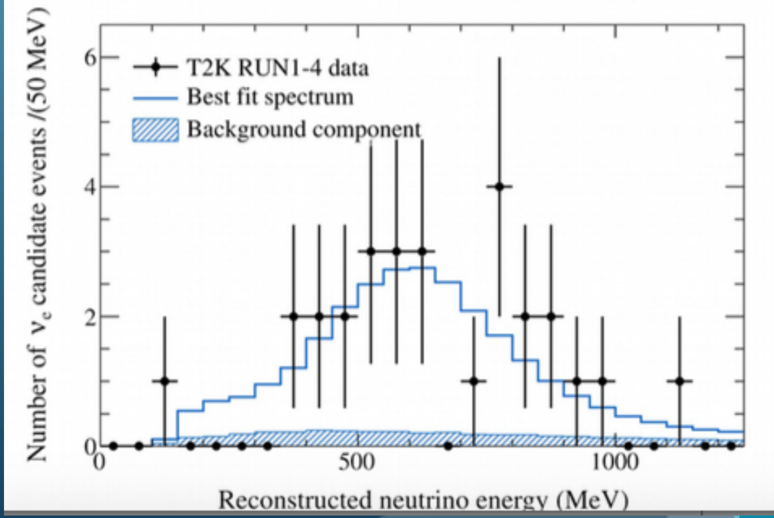
appearance $\nu_\mu \rightarrow \nu_e$ T2K

expected background: 4.64 ± 0.53

observed (2013):

28 events

7.3σ significance for non-zero θ_{13}



Reconstructed neutrino energy

Remember that ν_μ appearance was "visible" in SNO via NC interactions, but not direct observation